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A simple Technique for Determining the Maximum Ground Level Concentration of An Elevated Gaseous Release

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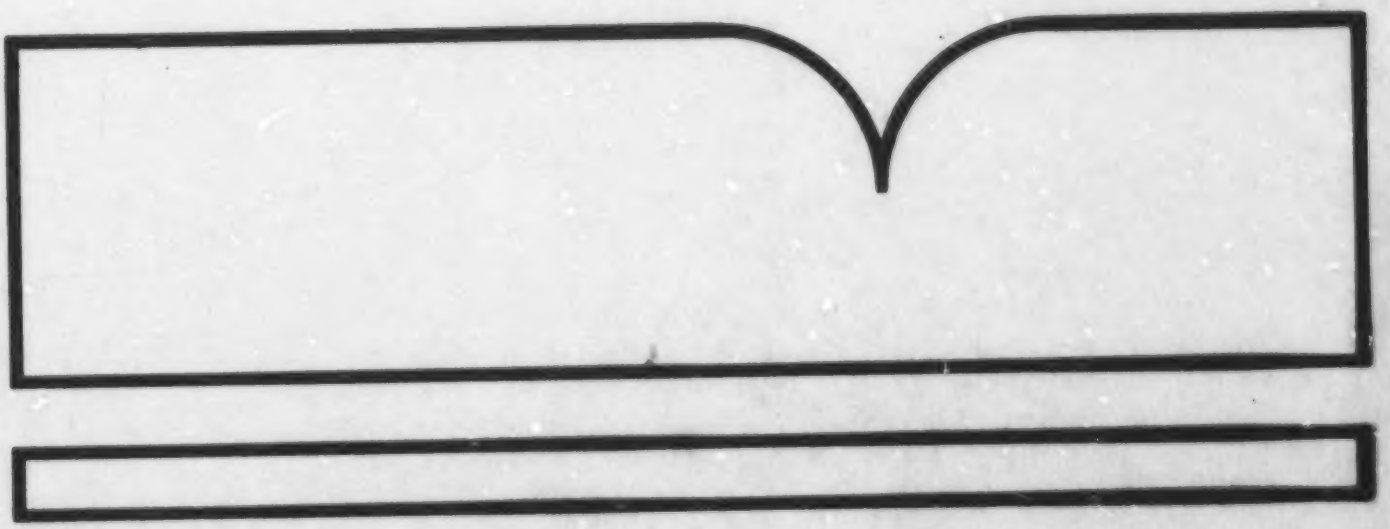

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16. ABSTRACT

The paper describes the development of a screening technique to determine the maximum 1 hour ground level concentration of a gaseous emission from a stack located in flat terrain. The method does not require the use of a computer and eliminates the usual trial and error calculations. An infinite mixing height is assumed. It involves a linear or quadratic solution of the gaussian plume diffusion as a function of the effective stack height and a linear approximation of the Briggs plume rise equation. The linear approximation of the former gives results that are within 5% of the gaussian plume results for stability criteria A, B, and C. For stability criterion D, the difference can be as great as 80%. If a quadratic estimation is used, the differences are less than 3% for stability criteria A, B, and C, and are within 18% for stability criterion D. A linear approximation is used for the Briggs plume rise equation. This gives results within 4% of the Briggs equation. Overall, this is a simple straightforward approximation which gives results which can be used to determine if more sophisticated procedures are necessary.

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A Simple Technique for Determining The Maximum Ground Level Concentration of An Elevated Gaseous Release

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A screening technique has been developed to determine the maximum one-hour ground level concentration of a gaseous emission from a stack located in flat terrain. The method does not require the use of a computer and eliminates the usual trial and error calculations. An infinite mixing height is assumed. It involves a linear or quadratic solution of the gaussian plume diffusion as a function of the effective stack height and a linear approximation of the Briggs plume rise equation. The linear approximation of the former gives results that are within 5% of the gaussian plume results for stability criteria A, B, and C. For stability criteria D, the difference can be as great as 80%. If a quadratic estimation is used, the differences are less than 3% for stability criteria A, B, and C, and are within 18% for stability criteria D. A linear approximation is used for the Briggs plume rise equation. This gives results within 4% of the Briggs equation. Overall, this is a simple straightforward approximation which gives results which can be used to determine if more sophisticated procedures are necessary.

One of the most important variables in determining whether a source emitting material from a stack is in compliance or not in compliance with air quality standards is the maximum ground level concentration of the pollutants that is likely to occur. Calculation of this concentration is generally based upon the gaussian plume diffusion model and the Briggs plume rise model.[1] Calculation of the maximum concentration depends on meteorological conditions, source operating conditions, and the physical dimensions of the stack from which the pollutants are emitted. This calculation, which has been made very straightforward by Budney,[1] Turner,[2] and Turner and Novak,[3] is still a time-consuming trial-and-error process. This paper presents a procedure that eliminates the trial-and-error and simplifies the rest. The end result is a screening tool involving some very simple equations from which the maximum ground level concentration can be calculated. From this it can be determined whether more sophisticated analyses are required.

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Mathematical Development for the Gaussian Plume Diffusion Equation

The form of the gaussian plume diffusion equation recommended for use by Turner[2] for a continuous elevated point source is:

$$\chi(x,y,z;H) = \frac{Q}{2\pi\sigma_y\sigma_z u}\exp^{*}\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\} \quad (1)$$

* Note: $\exp -a/b = e^{-a/b}$ where e is the base of natural logarithms and is approximately equal to 2.7183.

The values of σ_y and σ_z are given in graphic form by Turner as a function of distance downwind of the source and the atmospheric stability criteria.

The maximum ground level concentration will occur along the centerline of the plume. This concentration may be obtained by setting y and z equal to zero in Eq. (1). The result is

$$\frac{\chi u}{Q} = \frac{1}{\pi\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \quad (2)$$

The left side of Eq. (2) is a function of the effective stack height (H), the distance downwind from the source (χ), and the meteorological conditions. The effective stack height (H) is the sum of the physical stack height and the plume rise. Turner has plotted the $\chi u/Q$ as a function of the distance downwind of the source (x) and the effective stack height (H) for the six standard atmospheric stability criteria. From this solution the maximum value of $\chi u/Q$ was obtained for a given effective stack height (H) and atmospheric stability criteria (A, B, C, D). The equations are not developed here for atmospheric stability criteria E and F because the maximum ground level concentration for elevated releases in flat terrain never occurs during these criteria.[2]

By multiplying $\chi_{max}u/Q$ by H^2, the dimensionless function $\chi_{max}uH^2/Q = N_B$ was obtained. Table I gives N_B as a function of the effective stack height and the atmospheric stability criteria. For short stacks (50 m or less), it can be seen that this function is nearly constant. However, a linear relationship between N_B and H provides a closer fit. For part of the following development, it will be assumed that

$$N_B = \chi_{max}uH^2/Q = a + bH \quad (3)$$

Table I. N_B as a function of the atmospheric stability criteria and effective height. $N_B = \chi_{max}uH^2/Q$

Atmospheric stability criteria	Effective heights (m)									
	20	30	50	70	100	150	200	300	400	500
A	0.122	0.130	0.144	0.160	0.185	0.231	0.271	0.343	0.405	0.4763
B	0.130	0.132	0.137	0.144	0.154	0.166	0.175	0.189	0.200	0.209
C	0.139	0.139	0.139	0.139	0.139	0.140	0.140	0.141	0.142	0.1423
D	0.123	0.117	0.108	0.094	0.081	0.067	0.058	0.047	0.040	0.0194
E	0.102	0.095	0.079	0.066	0.052	0.037	0.029	0.016		
F	0.091	0.078	0.057	0.042	0.028	0.012				

The values of a and b for each atmospheric stability criterion were obtained from a least squares fit of the data in Table I and the values are given in Table II. The coefficient of determination, R^2, is also given in Table II. Since these values all exceed 0.85, this indicates a linear approximation accounts for most variation around the mean. Table III gives the result of using Eq. (3) to obtain N_B. The difference in the values in Tables I and III for stability criteria *A*, *B*, and *C* is less than 5%. These are the criteria where the maximum concentration is likely to be found. For the *D*, *E*, and *F* criteria, the differences are at times as great as 80%.

Table II. Constants for Eq. (3). $N_B = a + bH$

Atmospheric stability criteria	a	b	R^2
A	0.113	0.726×10^{-3}	0.995
B	0.133	0.169×10^{-3}	0.954
C	0.139	0.732×10^{-6}	0.957
D	0.110	-0.181×10^{-3}	0.853
E	0.095	-0.305×10^{-3}	0.883
F	0.093	-0.594×10^{-3}	0.926

If a better estimate is desired, a quadratic estimator can be used for N_B:

$$N_B = a + bH + fH^2 \qquad (4)$$

The values of the constants a, b, and f were again obtained from a least squares fit of the data in Table I. The results appear in Table IV. The coefficient of determination indicates that nearly all the variation around the mean is accounted for by the quadratic model. The calculated values of N_B obtained from these constants are given in Table V. All values in Table V for stability criteria *A*, *B*, and *C* are within 3% of the values in Table I. For the other criteria the errors are all less than 18%.

Plume Rise Equations

The effective stack height (H) is the sum of the physical stack height (h) and the plume rise (ΔH):

$$H = h + \Delta H \qquad (5)$$

Symbols Used

a = a coefficient defined by Eq. 3 or 4
a' = a coefficient defined by Eq. 9
b = a coefficient defined by Eq. 3 or 4
b' = a coefficient defined by Eq. 9
d = inside diameter of stack, m
$F = g v_s d^2 T_D/4$, m^4/sec^3
f = a coefficient defined by Eq. 4
$G = a' + b'F$
g = acceleration of gravity, m/sec^2
H = effective stack height, m
h = physical stack height, m
ΔH = plume rise, m
$N_B = \chi_{max}uH^2/Q$
P = atmospheric pressure at the top of the stack, mbar
Q = emission rate of pollutants, g/sec
R^2 = coefficient of determination
T_A = atmospheric temperature at top of the stack, K
$T_D = (T_S - T_A)/T_S$
T_S = temperature of exiting stack gas, K
u = wind velocity at stack height, m/sec
v_s = velocity of exiting gas stream, m/sec
y = crosswind distance, m
z = height above ground level, m
$\pi = 3.1416$
σ_y = the standard deviation in the crosswind direction of the plume concentration distribution
σ_z = the standard deviation in the vertical of plume concentration distribution
χ = concentration, g/m^3
χ_E = concentration of compound in exiting stack gas, g/m^3
χ_{max} = maximum ground level concentration, g/m^3
χ_{maxm} = peak feasible maximum ground level concentration, g/m^3

The equations which are most used today by EPA are those developed by Briggs.[3,4] These are, for atmospheric stability criteria *A*, *B*, *C*, and *D*:

$$\Delta H = 21.4F^{3/4}/u \text{ when } F < 55 \text{ m}^4/\text{sec}^3 \qquad (6)$$

Table III. N_B calculated using a linear equation with the constants given in Table II.

Atmospheric stability criteria	Effective heights (m)									
	20	30	50	70	100	150	200	300	400	500
A	0.1276	0.1349	0.1494	0.1640	0.1857	0.2221	0.2584	0.3310	0.4036	0.4763
B	0.1362	0.1379	0.1413	0.1447	0.1497	0.1582	0.1666	0.1835	0.2004	0.2173
C	0.1388	0.1389	0.1390	0.1392	0.1394	0.1398	0.1401	0.1409	0.1416	0.1423
D	0.1062	0.1044	0.1007	0.0971	0.0917	0.0827	0.0736	0.0556	0.0375	0.0194
E	0.0885	0.0854	0.0793	0.0732	0.0641	0.0488	0.0336	0.0031		
F	0.0810	0.0751	0.0632	0.0513	0.0335	0.0038				

Table IV. Constants for Eq. (4). $N_B = a + bH + fH^2$

Atmospheric stability criteria	a	b	f	R^2
A	0.101	0.922×10^{-3}	-0.398×10^{-6}	0.9996
B	0.124	0.307×10^{-3}	-0.281×10^{-6}	0.997
C	0.139	0.853×10^{-4}	-0.246×10^{-6}	0.959
D	0.127	-0.449×10^{-3}	0.545×10^{-6}	0.979
E	0.113	-0.701×10^{-3}	0.128×10^{-6}	0.989
F	0.114	-0.131×10^{-3}	0.423×10^{-6}	0.997

Table V. N_B calculated using a quadratic equation with the constants given in Table IV.

Atmospheric stability criteria	Effective heights (m)									
	20	30	50	70	100	150	200	300	400	500
A	0.119	0.128	0.146	0.163	0.189	0.230	0.269	0.342	0.406	0.462
B	0.130	0.133	0.139	0.144	0.152	0.164	0.174	0.191	0.202	0.207
C	0.139	0.139	0.139	0.139	0.139	0.140	0.140	0.141	0.142	0.142
D	0.116	0.114	0.106	0.0982	0.0875	0.0719	0.0589	0.0413	0.0345	0.0387
E	0.0991	0.0928	0.0808	0.0699	0.0544	0.0364	0.0238	0.0179		
F	0.0894	0.0784	0.0590	0.0430	0.0253	0.0128				

$$\Delta H = 38.7F^{3/5}/u \text{ when } F \geq 55 \text{ m}^4/\text{sec}^3 \quad (7)$$

where

$$F = gv_s d^2 T_D/4 \quad (8)$$

These equations may be linearized by determining the constants in the equation:

$$\Delta H = [a' + b'F]/u \quad (9)$$

These constants a' and b' are given below for various ranges of F:

For $10 < F < 55$
$a' = 62.3$
$b' = 6.88$
For $55 < F < 170$
$a' = 248$
$b' = 3.57$
For $170 < F < 400$
$a' = 445$
$b' = 2.44$

The linearized values of ΔH differ by less than 4% from the results of the Briggs equations (Eq. 6 and 7) for F between 15 and 400. Some comparisons are given in Table VI.

Mathematical Development

The mathematical development will initially be performed using the linear approximation for N_B. Then the procedure will be repeated using the quadratic approximation for N_B.

The pollutant mass flow rate can be expressed as:

$$Q = \pi v_s d^2 \chi_E/4 \quad (10)$$

If Eq. (5), (9), and (10) are substituted into Eq. (3) the result is

$$N_B = \frac{4\chi_{max} u[h + (a' + b'F)/u]^2}{\pi v_s d^2 \chi_E} = a + b\,[h + (a' + b'F)] \quad (11)$$

After this substitution, if Eq. (11) is solved for the maximum concentration along the centerline, the result is:

$$\chi_{max} = \frac{\pi v_s d^2 \chi_E [a + b[h + (a' + b'F)/u]]}{4u[h + (a' + b'F)/u]^2} \quad (12)$$

For a given stack, a given atmospheric stability criterion, and an emission concentration, stack temperature, air temperature, air velocity, and air pressure at the top of the stack, the only variable is u. The maximum possible concentration can then be obtained by taking the derivative of the above with respect to u, setting the derivative equal to zero, solving for u, and substituting this back into Eq. (12).

The peak maximum is

$$\chi_{maxm} = \frac{\pi d^2 \chi_E v_s}{16(a' + b'F)} \left[\frac{(a + bh)^2}{ah}\right] \quad (13)$$

This maximum occurs when:

$$u = (a' + b'F)\frac{(a - bh)}{(a + bh)h} \quad (14)$$

Table VI. $u\Delta H$ for Briggs equation and Eq. 9 as a function of F.

F	Briggs	Equation 9	Diff.
10	120.5	131.0	−10.5
15	163.3	165.4	−2.1
20	202.6	199.8	2.8
25	239.5	234.2	5.3
30	274.6	268.6	6.0
40	340.8	337.3	3.5
50	402.9	406.0	−3.1
60	451.4	462.9	−11.5
70	495.2	498.6	−3.4
80	536.5	534.3	2.2
90	575.8	570.0	5.8
100	613.4	605.7	7.7
120	684.3	667.2	7.1
140	750.6	748.6	2.0
160	813.2	820.1	−6.9
180	872.7	885.0	−12.3
200	929.7	933.9	−4.2
220	984.4	982.8	1.6
240	1037.1	1031.7	5.4
260	1088.2	1080.6	7.6
280	1137.6	1129.5	8.1
300	1185.7	1178.4	7.3
320	1232.5	1227.3	5.2
340	1278.2	1276.2	2.0
360	1322.8	1325.1	−2.3
380	1366.4	1374.0	−7.6
400	1409.1	1422.9	−13.8

For atmospheric stability criteria A through D, a known stack temperature, a known atmospheric temperature, and a specific stack operating in a given way, the only variable is $(a + bh)^2/ah$. This function is given in Table VII. As can be seen, except for stack heights less than 20 m, the maximum ground level concentration occurs during unstable conditions (A stability). This agrees with what has been observed.

The maximum value of the ground level concentrations occurs when

$$a(h - G/u) + bh(h + G/u) + f(h + G/u)^3 = 0 \quad (17)$$

where

$$G = a' + b'F \quad (18)$$

Table VII. The solution for a major function in Eq. (13). $(a + bh)^2/ah$

Atmospheric stability criteria	Effective heights (m)						
	10	20	30	50	100	200	400
A	0.0128	0.00720	0.00536	0.00395	0.00305	0.00295	0.00360
B	0.0136	0.00698	0.00477	0.00301	0.00169	0.00105	0.000756
C	0.0139	0.00695	0.00464	0.00279	0.00140	0.000708	0.000361
D	0.0106	0.00513	0.00331	0.00185	0.000786	0.000247	0.000032
E	0.00885	0.00414	0.00257	0.00133	0.000434	0.000080	0.000020
F	0.00814	0.00353	0.00202	0.000860	0.000121	0.000036	0.0000066

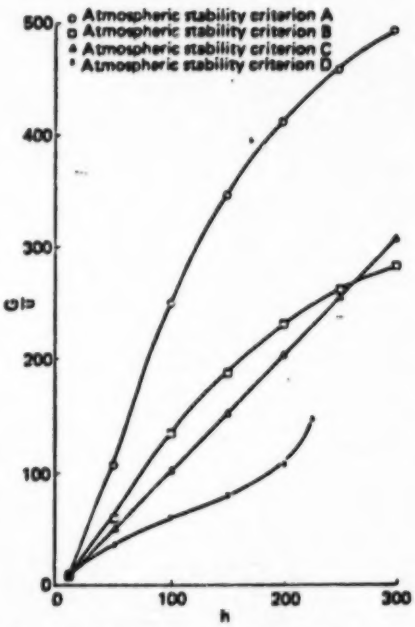

Figure 1. The solution to Eq. (17). G/u vs. h

From Table VII it can also be seen that for a stack having given exiting conditions (d, χ_E, v_s, and T_D are constant), the maximum concentration, under different atmospheric stabilities, for 20 m stacks does not differ by more than a factor of two. This difference increases with stack height. It should be further noted that, for the A stability criterion and a stack having given exiting conditions, the maximum ground level concentration does not differ by more than a factor of four.

For the quadratic solution the equivalent equation to Eq. (12) is:

$$\chi_{max} = \frac{\pi v_s d^2 \chi_E [a + b(h + G/u) + f(h + G/u)^2]}{(h + G/u)^2} \quad (15)$$

This can be alternatively expressed as:

$$\chi_{max} = \frac{\pi}{4} \frac{v_s d^2 \chi_{EG} [a - f(h + G/u)^2]}{u^2 h (h + G/u)^2} \quad (16)$$

Eq. (17) must now be solved and the resultant wind speed (u) substituted into either Eq. (15) or (16) to obtain the maximum ground level concentration. The solution to Eq. (17) has been obtained and the results have been plotted in Figure 1 for atmospheric stability criteria A, B, C, and D. The solution to Eq. (15) has been plotted in Figure 2. Figure 2 shows again that, except for stack heights less than 20 m, the A atmospheric stability criterion gives the highest maximum concentration.

Anyone using this solution should check that the velocity associated with the maximum concentration is a reasonable one. If it is not, then the nearest suitable velocity should be assumed and substituted into Eq. (12) or (15). Under these circumstances atmospheric stability criteria other than A should be investigated.

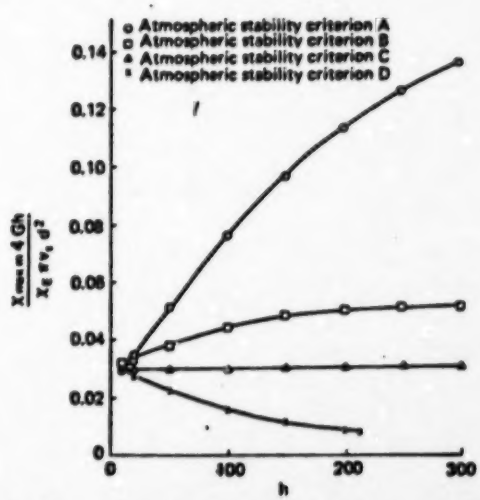

Figure 2. The quadratic solution for atmospheric stability criteria *A*, *B*, *C*, and *D*.

The following example illustrates how the equations which were developed can be used.

Example 1

Suppose a plant has a stack that is 50 m tall with a diameter of 4 m. Its emissions leave at 18 m/sec and 450°K. Assume that, at the top of the stack, the atmospheric pressure is 1013 mbars (1 atmosphere) and the atmospheric temperature is 293

K (20°C). What is the ratio of the maximum ground level concentration to the exiting concentration of a gaseous pollutant?

If a linear approximation to the Briggs equation is used, the appropriate equations are (8), (13), and (14).

$$F = 9.8 \times 18 \times (4)^2 (450 - 293)/(450 \times 4)$$
$$= 246 \text{ m}^4/\text{sec}^3 \quad \text{from (Eq. (8)}$$

$$\frac{\chi_{maxm}}{\chi_E} = \frac{\pi\chi(4)^2 \times 18}{16[445 + (2.24 \times 246)] \times 50}$$
$$\times \left[\frac{(0.113 + 7.26 \times 10^{-4} \times 50)^2}{0.113}\right] = 0.000223 \quad \text{from Eq. (13)}$$

$$u = \frac{[445 + (2.24 \times 246)][0.113 - (7.26 \times 10^{-4} \times 50)]}{[0.113 + (7.26 \times 10^{-4} \times 50)]50}$$
$$= 10.2 \text{ m/sec} \quad \text{from Eq. (14)}$$

If the quadratic estimators are used for N_B, Figures 1 and 2 apply and Eq. (6) or (7) will be used to obtain G instead of the linear approximation. Since F is over 55 m^4/sec^3, Eq. (7) applies:

$$G = u\Delta H = 38.7\,(246)^{0.6} = 1053 = (a' + b'F)$$

so

$$u = 1053/106.62 = 9.88$$

From Figure 2 for atmospheric stability criteria A

$$\frac{\chi_{maxm}}{\chi_E} \frac{4Gh}{\pi v_s d^2} = 0.5115$$

$$\frac{\chi_{maxm}}{\chi_E} = \frac{0.05115(3.14)(18)(4)^2}{4(1053)50} = 0.000220$$

This will now be compared with the solution obtained using the methods presented by Turner.[2] If Briggs equation is used, $u\,\Delta H = 1053$. If $u = 9.9$ m/sec, $\Delta H = 1053/9.9 = 106$, and $H = h + \Delta H = 50 + 106 = 156$. From Table 3-5A, reference 2:

$$\left(\frac{\chi u}{Q}\right) \max = 0.97 \times 10^{-5}.$$

The result is:

$$\frac{\chi_{max}}{\chi_E} = \frac{0.97 \times 10^{-5}\pi v_s d^2}{4u}$$
$$= \frac{0.97 \times 10^{-5}(3.14)(18)(4)^2}{4(9.9)} = 0.000221$$

When the above is repeated for different values of the wind speed, the results are:

$$\text{if } u = 8.9 \text{ m/sec}, \frac{\chi_{max}}{\chi_E} = 0.000222;$$

$$\text{if } u = 8.5 \text{ m/sec}, \frac{\chi_{max}}{\chi_E} = 0.000223;$$

$$\text{if } u = 8 \text{ m/sec}, \frac{\chi_{max}}{\chi_E} = 0.000219.$$

The minimum value of the concentration ratio is therefore equal to 0.000223. The linear predicted value is the same as this value and the quadratic is within 2%.

Conclusions

The maximum ground level concentration of an emission from a stack located in a flat terrain, assuming the gaussian plume diffusion equation and the Briggs equations for plume rise, has been determined to be:

$$\chi_{maxm} = \frac{0.0222d^2\chi_E v_s(1 + 0.0064h)^2}{h[a' + gb'v_s d^2(T_S - T_A)/4T_S]}$$

This occurs when:

$$u = [a' + b'gv_s d^2(T_S - T_A)/4T_S]\left[\frac{1 - 0.0064h}{1 + 0.0064h}\right]\frac{1}{h}$$

If $10 < gv_s d^2(T_S - T_A)/4T_S < 55$ then $a' = 62.3$; $b' = 6.88$.

If $55 < gv_s d^2(T_S - T_A)/4T_S < 170$ then $a' = 248$; $b' = 3.57$.

If $170 < gv_s d^2(T_S - T_A)/4T_S \leq 400$ then $a' = 445$; $b' = 2.44$.

The atmospheric stability classification which gives the highest ground level concentration is usually classification A. The equations above are for classification A. The text also gives the maximum ground level concentrations for atmospheric stability classifications B, C, and D.

The above is also based on a linear approximation. A more precise quadratic approximation can be obtained from Figure 2.

Acknowledgments

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